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A preliminary comparative performance evaluation of highly efficient Waste-to-Energy plants

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Abstract

When looking for sustainable energy systems, Waste-to-Energy plants play a relevant role. Therefore performance evaluation of these plants in order to increase their efficiency is of great relevance to the field of engineering. In the present paper, highly efficient Waste-to-Energy plants are modeled and analyzed from the thermodynamic and technological points of view. Four existing plants constructed in Amsterdam/the Netherlands, Reo Nord/Denmark, Brescia/Italy and Germany were considered. The different methods aiming at increasing the efficiency adopted in these plants have been discussed and compared by using available data in the literature. The performance evaluation was carried out using a proprietary code developed at Politecnico di Milano. A sensitivity analysis was performed to investigate the effects of the plant size, condenser pressure, oxygen content and flue gas temperature at boiler exit on the efficiency of the plants. The results show that adopting a new configuration for steam cycle increases the efficiency of the plant, thus also reducing the corrosion of boiler tubes. It is also demonstrated that the proposed configuration leads to a net lower heating value efficiency of 33%.

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Keywords: Waste-to-Energy, Steam, Corrosion, High-Efficiency, Simulation

1. Introduction

Bringing a long term solution in solid waste management that are environmentally safe, socially acceptable and cost effective is a challenging task. During the last decades, the main attention in Waste-to-Energy plants has been primarily on lowering emissions and this goal has been achieved by using costly flue gas treatment units and the discharge rate of pollutants is very low in up-to-date Waste-to-Energy facilities compared with fossil fuel or biomass

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based combustion plants [1]. To counterbalance the increase in cost of the Waste-to-Energy plants, the research focuses mainly on improving the overall efficiency of the plants by using higher steam parameters (pressure and temperature) in the Rankine cycle, which are limited by the high-temperature corrosion of boiler tubes and combustion technology [2, 3]. This is because municipal solid waste contains high concentration of corrosive elements such as alkali and heavy metals and particularly chlorine. During combustion most of the chlorine is released as HCl and mainly alkali and heavy chlorides (NaCl, KCl, $PbCl_{2...}$) are formed in the combustion process. During flue gas cooling, these chlorides condense and deposite partly on boiler tubes causing chlorine induced corrosion. This corrosion increases significantly with temperature of boiler tubes [4, 5]. Generally, feedstock compositions, poor boiler design, variation in flue gas composition and process parameters such as metal temperature, flue gas temperature, flue gas velocity have been identified as potential causes of corrosion in Waste-to-Energy plants [6-8]. Some protection methods that have already been proposed and demonstrated are adoption of Inconel alloy 625 cladding and composite tubes, different designs of boilers, injection of chemicals into combustion chamber, longer flue gas residence time and lower flue gas speed [5, 9-10].

Due to these corrosion problems many European Waste-to-Energy (WtE) facilities operate in the range of 400-425 ^{0}C / 40-50 bar [11]. This is an economic compromise between acceptable corrosion rates and maximum power generation. There are some exceptional WtE plants that use high superheater temperatures as shown in Fig. 1.

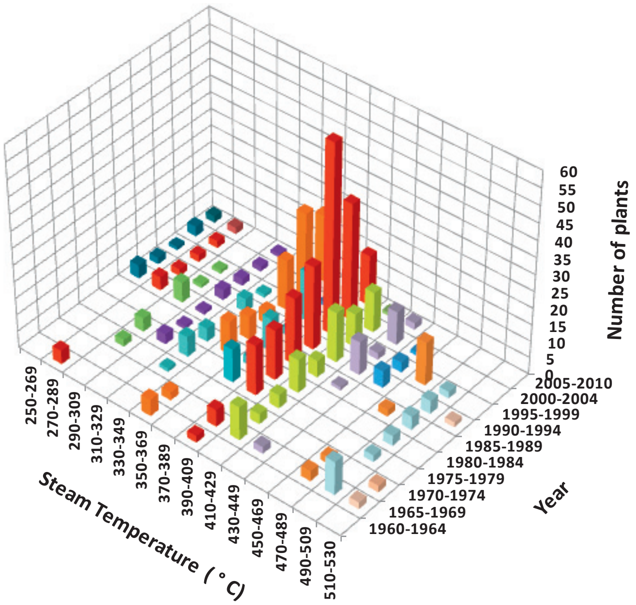

Fig. 1. Steam temperature; grate fired plants in Europe [11].

However, these WtE plants required longer downtime periods for maintenance to replace superheater bundles [12]. Higher efficiencies can also be achieved if superheating is realized in external fossil-fired boilers, which do not have the corrosion limitations of waste-fired boilers as implemented in Bilbao/Spain and Mainz/German where Municipal solid waste pregenerated steam is further superheated from 400 ^{0}C to 550 ^{0}C by the hot off gas after the gas turbine of a natural gas fired combined-cycle power plant [13]. However, the aforementioned configuration is less economic due to relatively high cost of natural gas and it is also less environmental friendly due to combustion of natural gas.
The first highly efficient WtE plant installed in Amsterdam uses higher steam temperature/pressure together with an intermediate superheating using steam from the boiler drum and achieves a net electrical efficiency of 30 % [12]. The other new idea to further enhance the efficiency of WtE plants is based on dividing the flue gas from grate into two fractions. Then, the lower corrosive part of the flue gas is directed to a separate superheater section, where it further increases the steam temperature [14, 15]. In the technology proposed by the Karlsruhe institute of technology research centre, the waste combustion takes place in the main furnace and a fraction of the produced gas is extracted prior to enter the flue gas burnout zone [4].This fuel gas passes a small bypass system equipped with subsequently arranged sections: gas cooling, gas cleaning, combustion and further superheating of the steam from the main boiler.

To the best of our knowledge, modelling of Waste-to-Energy plants is made difficult due to scarce available data in the literature. Even though experimental measurements are irreplaceable, it is believed that a reliable model can be a cheap and efficient tool to understand critical points and details of the plant operation.

Several studies have been carried out involving modeling analysis of Waste-to-Energy plants. Simulation of a Waste-to-Energy plant was carried out by Consonni [16] to investigate the effect of various strategies for energy recovery from Municipal solid waste. Consonni and Viganò [17] also developed a WtE plant model for grate based and gasification based WtE Plant by means of proprietary simulation software [18]. Touš et al.[19] performed a Waste-to-Energy systems modelling using in-house developed software (W2E) for the performance analysis of technologies in the field of thermal treatment of waste. Manca et al.[20] simulated incineration plants to test advanced control strategies. However performance evaluation of Waste-to-Energy plants in order to increase their efficiency is of great relevance to the field of engineering.

The aim of the paper is to model, analyze and compare different highly Waste-to- Energy plants and to propose a new configuration. The models have been developed by generating a detailed mass/energy balance for the components of each plant. Then the performance results are analyzed and compared to the conventional WtE plant based on thermodynamic and technical criteria. Lastly, a new configuration is proposed which results in enhancing the overall efficiency of the plant while satisfying technical constraints mainly due to corrosion problems.

2. Systems of Interest and strategies

This paper focuses on four state-of-the-arts and highly efficient grate based direct combustion technologies considering four different WtE facilities built in Amsterdam/ the Nethrlands, Reo Nord/Denmark, Brescia/Italy and Germany. These plants are among the few that have operated commercially and for which some data for model verification are of public domain. The performances of these technologies are compared with the state-of –the-art conventional Waste-to-Energy plant with live steam at 40 bar and 400 ^{0}C in the Rankine steam cycle.

2.1. SteamBoost (the flue gas split concept)

The Babcock & Wilcox Company has developed a new approach to improve the net electrical efficiency of WtE plants and received world patent [13]. The basic idea of this model is to divide the flue gas from the grate into two fractions having one fraction of the flue gas with a high corrosive content of chlorine and another fraction with a low chlorine concentration since the corrosivity of the flue gas varies significantly over the grate length. The low corrosive part of the flue gas may be directed to a separate superheater section to increase the steam temperature and thereby boosting the electrical efficiency of the plant [13]. Typically in conventional WtE plants which generate steam at 40 bar/400 $^{\circ}$C, electrical efficiency of approximately 24 % (with respect to LHV value) can be achieved [11]. When using an extra superheater using the flue gas split concept, the steam data is increased to 50 bar/500 $^{\circ}$C, thereby increasing efficiency by 3% [14]. This method is applied in Denmark, Reno-Nord WtE CHP plant.

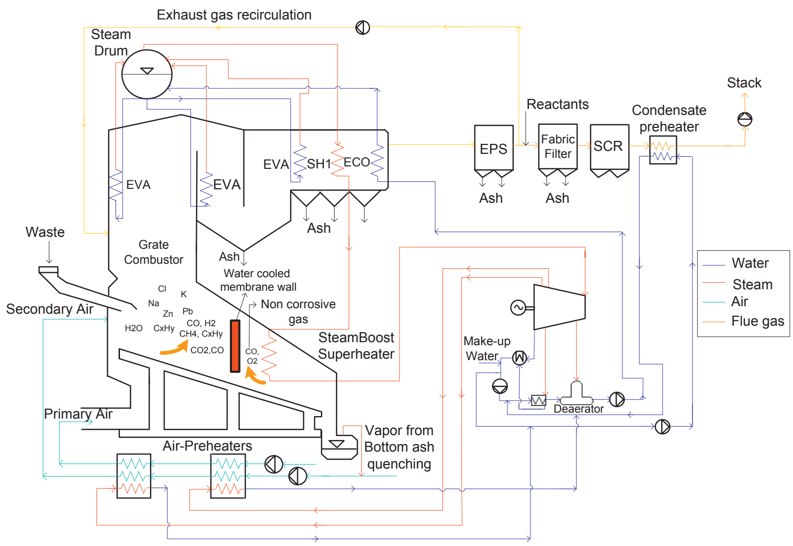

Fig. 2. Schematic configuration of waste fired power plant with two stage furnace and SteamBoost superheater.

2.2. The Amsterdam High efficiency Waste-to-Energy plant

A classic method used by Amsterdam Waste-to-Energy plant to improve efficiency is to reheat part of the steam after the high-pressure turbine using a steam-steam shell-and-tube heat exchanger to obtain a net electrical efficiency of 30 % and availability of over 90% by using Inconel 625 as boiler cladding [2, 3] .
As illustrated in Fig. 3, it is equipped with a MARTIN horizontal grate combustion system. In this plant, the steam pressure is increased from the typical 40 bar to 130 bar. Another new component is the intermediate reheater in which the saturated steam from the boiler drum is used to reheat the steam , which comes out of the high pressure turbine , from 14 bar/195 ^{0}C to 14 bar/ 320 ^{0}C [3]. The temperature of the live steam at the outlet of the superheater is 440 ^{0}C. The main advantage of this configuration is its high energy efficiency due to the high pressure and the reheating combined with modest superheater temperature of 440 ^{0}C. Combustion takes place at an excess air ratio of 1.4 in order to reduce the flue gas losses. A portion of the flue gas is recirculated back into the lower part of the boiler which reduces the temperature and improves the mixing in the post combustion zone. In this plant, a condensing pressure of 0.03 bar is used.

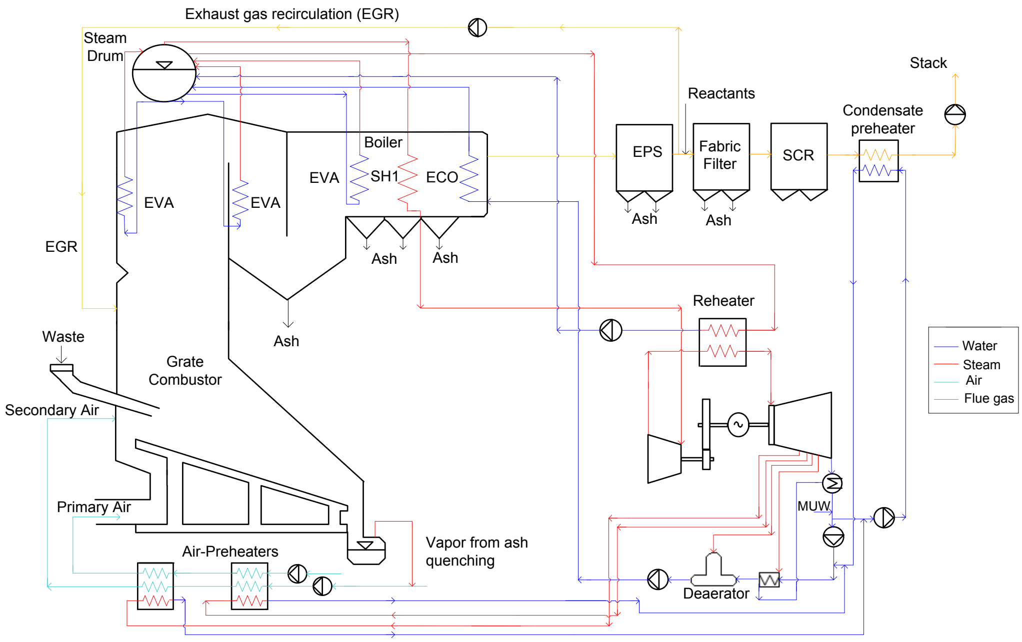

Fig. 3: Water-steam schematic diagram of 130 bar/ 440 °C system with intermediate reheating [3].

2.3. The Bilbao Waste-to-Energy Plant concept

The Waste-to-Energy plant built in Bilbao (Spain) has been designed to maximize the net electrical efficiency by further superheating the steam generated in a MSW grate combustor using the hot off gas after the gas turbine of a natural gas combined cycle power plant. Therefore, increasing steam temperature externally in the Rankine cycle improves the net electric efficiency of WtE plant and reduces corrosion of boiler tubes [13]. The waste boiler is operated with 100 bar pressure and superheating to 540 °C takes place in the boiler of an integrated combined cycle power plant. In this way, the overall plant efficiency is increased to 42 % [21]. In this paper, this option is not considered.

2.4. The Brescia Waste-to-Energy plant

The Brescia Waste-to-Energy plant of Italy yields a net electrical efficiency of more than 27 % through increased steam parameters, reduced flue gas losses, minimized in-plant consumption, combustion air preheating and combustion with low excess air [21].

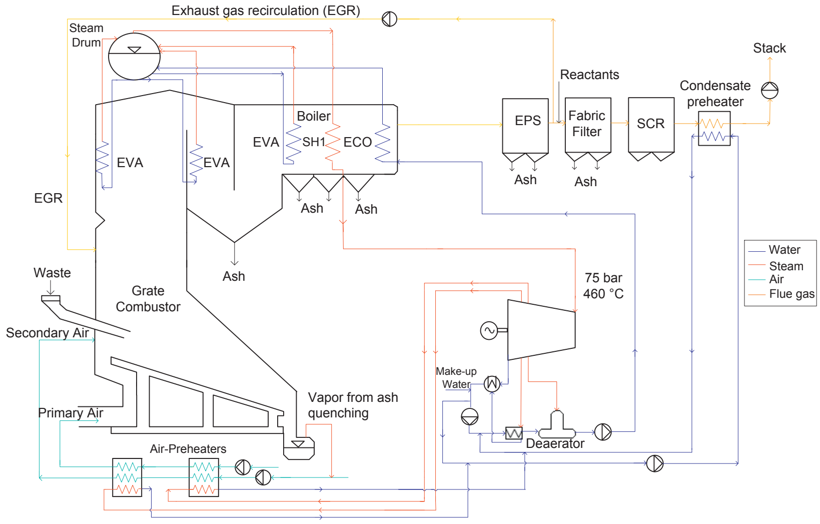

Fig. 4. The Waste-to-Energy plant of Brescia, Italy [22].

2.5. A new processes for high efficient power generation in WtE plants – bypass of fuel gas

The Karlsruch institute of technology research center has proposed a new technology for WtE plants [4]. Combustion of solid fuel takes place in the main furnace and a fraction of the formed gas can be extracted prior entering the flue gas burnout zone. This fuel gas then passes a small bypass system equipped with subsequently arranged sections: gas cooling, gas cleaning, combustion and further superheating of the regenerated steam from the main boiler. In this configuration (Fig. 5), the temperature of the steam leaving the main boiler at 120 bar / 400 ^{0}C is further increased up to 540 ^{0}C by burning the extracted fuel in a small combustion chamber and utilizing the generated heat for improved superheating of the pregenerated steam. It is noteworthy that, to use the extra superheater at this high temperature by avoiding corrosion the extracted fuel has to be cleaned prior to combustion [4]. Therefore, the extracted fuel is cooled down to about 400 ^{0}C using a heat exchanger to preheat the air.

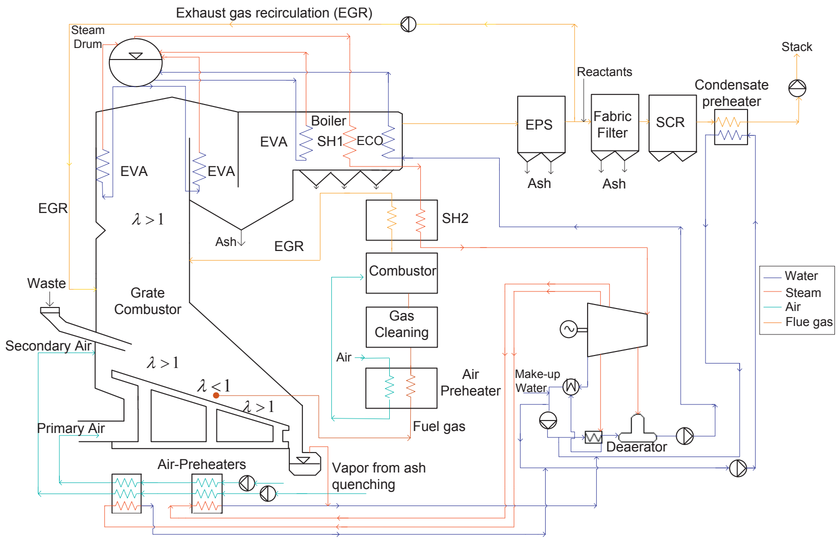

Fig. 5. Schematic diagram of Waste-to-Energy plant using bypass concept

2.6. New configuration

In this new configuration (Fig.6), the steam parameters (temperature/pressure) are further increased to 135 bar /540 ^{0}C and intermediate superheating is used to increase the temperature up to 400 ^{0}C to achieve higher efficiency. This is a compromise between the two technologies proposed by Amsterdam WtE plant and the by pass concept together with one additional intermediate reheater. In brief, a portion of fuel gas extracted from the combustion chamber, as stated earlier is combusted in a separate combustion chamber. The flue gas is then divided into two portions. The first one is used to further increases the main inlet temperature up to 540 ^{0}C whereas the second one is used to increase the intermediate steam temperature up to 400 ^{0}C. It is noteworthy that the steam which comes out of the high pressure turbine is first heated by steam-steam heat exchanger up to 320 ^{0}C with the help of steam that comes directly from a steam drum like Amsterdam WtE plant. Optimization of the proposed WtE plant has been performed by using higher steam parameters (135 bar/ 540 ^{0}C), combustion air preheating by extracting steam from HP and LP turbine upto 155 ^{0}C, combustion with low excess air (5.5 to 6 % O_2 content), low pressure/temperature of steam condensation up to 0.03 bar/24 ^{0}C, low flue gas temperature at boiler exit and regenerative condensate preheating.

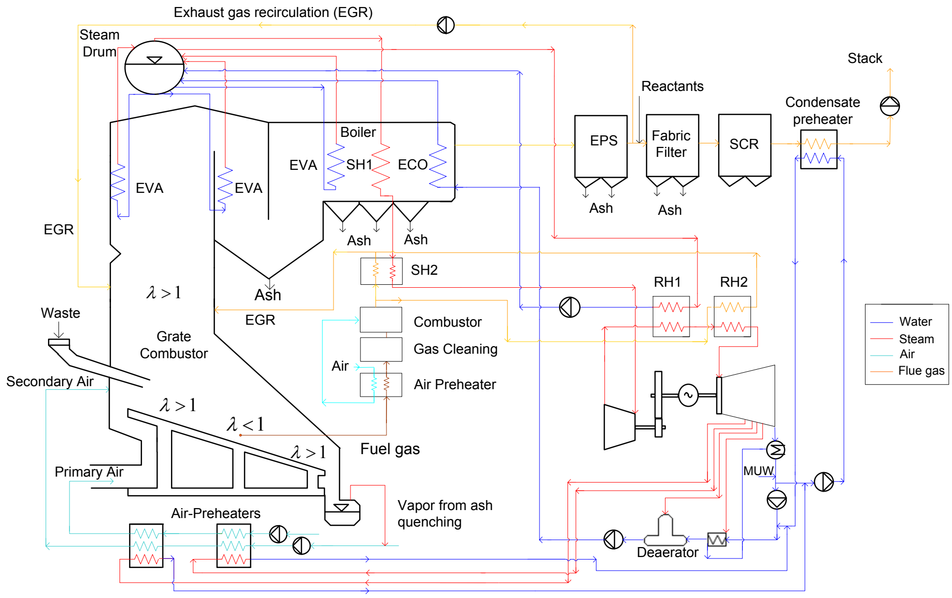

Fig. 6. Schematic diagram of the new configuration.

3. Modelling and assumptions

This section discusses the modelling approach and the assumption adopted to simulate the Waste-to-Energy plants presented in the previous section. Mass and energy balances, along with the overall power plant performance, has been carried out by a proprietary computer code (GS) developed by the Gecos group at the Department of Energy of Politecnico di Milano [18]. The code is a powerful and flexible tool that can be used to accurately predict the performance of a very wide variety of chemical processes and systems including coal gasification, chemical reactors, fuel cells, Waste- to-Energy plants and essentially all the processes present in advanced plants for power generation.

3.1. Model Calibration

As previously anticipated, few technical information about each technology is available in the literature. Therefore, the model of each technology has been calibrated to reproduce as closely as available data on operating conditions and the performances of actual plants. These data come from different literatures [3, 4, 12-18]. Unfortunately they are not enough; therefore, some assumptions have been required. Because of the uncertainties related to some assumptions, a sensitivity analysis was performed on the most important parameters of the plant.

3.2. Main assumptions

This section discusses the main assumptions adopted to simulate WtE plants presented in the previous section. First, each of the technologies has been calibrated and then they have been used to evaluate the performance of each plant under the following operating conditions: same waste composition (Table 1), same treatment capacity and operating hours, different steam cycle configurations, and same flue gas temperature at boiler exit, same O_2 content at boiler exit and stack and same flue gas treatment systems as shown in table 2.

Table 1. Waste composition and heating value used for all simulations [17].

Reference waste		
Composition (% by mass on wet basis)	C	27.5
	Cl	0.27
	F	0
	H	4.23
	N	0.64
	O	15.44
	S	0.04
	Ash	17.0
	Moisture	34.89
	Total	100.0
Heating value (MJ/kg)	Lower (LHV)	10.38
	Higher (HHV)	12.15

Table 2. Main assumptions adopted for plant simulations

	Conventional WtE plant- A	**Amsterdam WtE plant- B**	**Brescia WtE plant- C**	**SteamBoost- D**	**Bypass concept- F**	**New Configuration**
Reference conditions						
Temperature (°C)	15	15	15	15	15	15
Pressure (bar)	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325
Humidity (%)	60	60	60	60	60	60
Plant						
Treated waste (t/y)	500,000	500,000	500,000	500,000	500,000	500,000
Equivalent working hour (h/y)	7850	7850	7850	7850	7850	7850
Waste flow rate (kg/s)	18.5	18.5	18.5	18.5	18.5	18.5
Rated thermal input, MW_{LHV}	186	186	186	186	186	186
Combustor						
Air preheating temperature	150	150	150	150	150	150
Losses for unburnt carbon % LHV	1.5	1.5	1.5	1.5	1.5	1.5
Thermal losses, % LHV	1	1	1	1	1	1
O_2 at boiler exit, % Vol. dry	6.0	6.0	6.0	6.0	6.0	6.0
Boiler						
Flue gas temp. at boiler exit (°C)	180	180	180	180	180	180
Steam cycle						
Steam Temp. (°C) at turbine inlet	400	440	460	500	540	540
Steam pre. (bar) at turbine inlet	40	130	80	80	120	135
Steam Temp. (°C) at HP turbine outlet	226.09	195	252.08	252.08	-	400
Condensing pressure (bar)	0.03	0.03	0.03	0.03	0.03	0.03
O_2 at stack, % vd	5.0	5.0	5.0	5.0	5.0	5.0

4. Results and discussion

Table 4 summarizes the results of the WtE plants previously introduced. The performance of the reference conventional Waste-to-Energy plant is shown in the first column, while the other five columns present the approaches adopted by WtE plants of Amsterdam, SteamBoost concept, Brescia, bypass concept and the new configuration respectively. The results of the analysis showed that going from the reference case (40 bar, 400 ^{0}C) to higher steam conditions (135 bar, 540 ^{0}C) increases the efficiency from 27.25 % to 33.19 % as shown in Table 3 and reduce also the corrosion of boiler tubes as shown in Fig. 7. Considering the configuration adopted by Brescia WtE plant, the steam is raised to 70 bar/ 460 ^{0}C but this condition inevitably enhances corrosion since a large part of the superheater is in the transition area. Instead, in the steamBoost concept, the steam condition is further increased to 80 bar/ 400 ^{0}C followed by superheating to 500 ^{0}C. Since superheating is performed in the less corrosive part of the combustion chamber as mentioned before, the effect of corrosion is very less with a 2.5 % gain in efficiency. The simulation result for the Amsterdam WtE plant shows a net electrical efficiency of 31.21 %, slightly higher than the actual plant data as reported in Berlo [3].The difference is due to assumptions: (i) on waste compositions, (ii) on the details of steam turbine configurations and (iii) On auxiliary consumptions.

Based on the simulation result, in the bypass concept, the steam leaving the main boiler at 120 bar / 400 ^{0}C is increased up to 540 ^{0}C as mentioned before without corrosion problem in the superheater and with a gain of 5 % in efficiency compared to the reference case. However, the pressure can be further increased in this configuration to take advantage of Amsterdam WtE plant together with using two intermediate reheaters. In this way the steam parameters are increased to 135 bar/ 540 ^{0}C with intermediate reheating up to a temperature of 400 ^{0}C. This new configuration can give us: High tolerable steam quality (x = 0.9) in the LP turbine, without corrosion problem in the superheater and high efficiency compared to all the cases considered.

Table 3. Some of the main simulation results

	Conventional WtE plant	Amsterdam WtE plant	SteamBoost	Brescia WtE plant	Bypass concept	New Configuration
Thermal input, MW_{LHV}	186	186	186	186	186	186
Treatment capacity, t/y	500,000	500,000	500,000	500,000	500,000	500,000
Steam Production	239.59	219.50	213.83	232.05	187.46	198.88
Boiler Efficiency, %LHV	0.9095	0.9047	0.9095	0.9095	0.9121	0.8938
Gross Electric power, MW_E	58.85	66.96	63.59	60.53	67.03	70.84
Net Electric power, MW_E	52.13	59.27	56.68	53.44	59.72	63.51
Net Electric Efficiency, %LHV	**27.25**	**30.97**	**29.62**	**29.73**	**31.21**	**33.19**
R1 index	**0.75**	**0.854**	**0.8168**	**0.77**	**0.8606**	**0.9152**

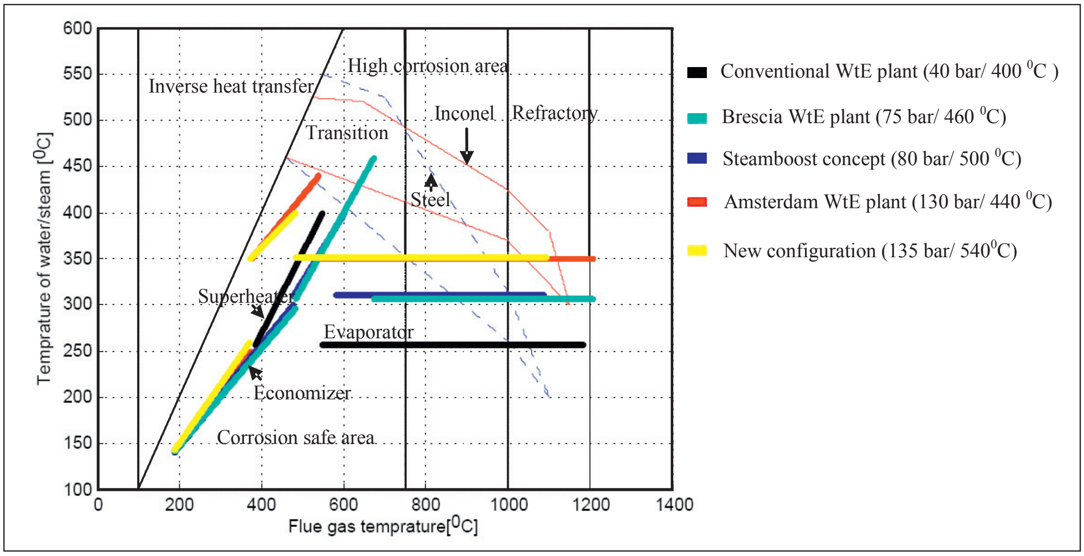

Fig.7. Corrosion diagram

5. Sensitivity analysis

The sensitivity analysis is carried out for the proposed configuration to investigate the effect of flue gas temperature at boiler exit, amount of excess air, variation of plant size and variation of condenser pressure on the overall net electrical efficiency of the plant. It has to be noted that if not specified, the parameters which is used in this sensitivity analysis assume the default values as shown in table 2 for the proposed configuration.

5.1. Flue gas temperature at boiler exit

Fig. 8. shows the increase in net electric efficiency of the plant as the boiler outlet flue gas temeparture decreases for two different values of condenser pressure. This exit temperature of the flue gas from the boiler is limited by aggressive compounds condensation. The typical outlet temperatures for most WtE plants is about 180 ^{0}C.

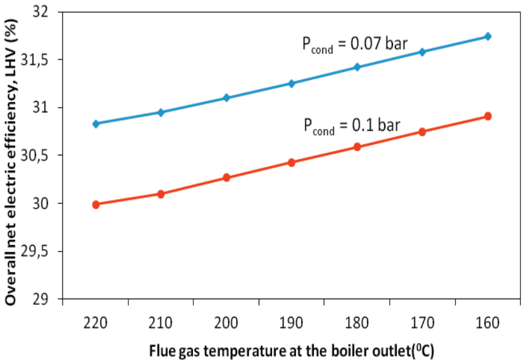

Fig. 8. Net electric efficiency vs. flue gas temperature at the boiler outlet for two different condenser pressure.

5.2. Excess air

The net electric efficiency is negatively influenced by high excess air as shown in Fig. 9. The amount of excess air determines the exaust gas losses and the power consumed by the induced fan. High excess air means , significant amount of exaust gas are discharged and thus raising the auxilary power consumption.

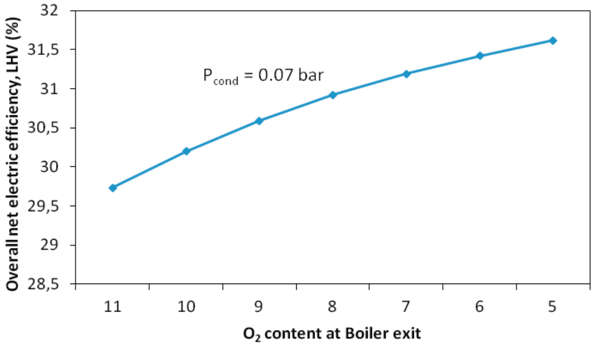

Fig. 9. Net electric efficiency vs. O_2 content at the boiler exit for a condenser pressure of 0.07 bar.

5.3. Variation of plant size

Fig. 10. shows the variation of the overall net Electric efficiency with plant size. It is demonstrated that the overall efficiency of Waste-to-Energy plants are significantly affected by plant size. Improvements in steam cycle efficiency, sophisticated design and improved operating parameters are the main factors for the increasing trend of the efficiency of large Waste-to-Energy plants.

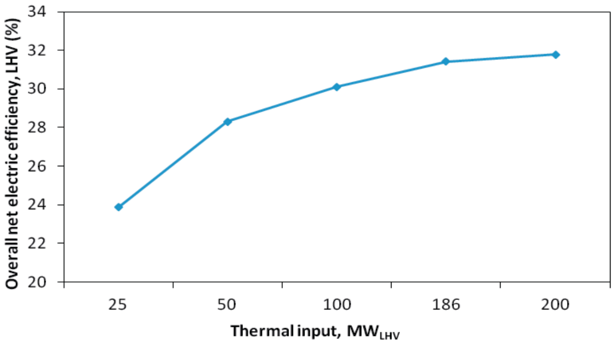

Fig. 10. Net electric efficiency vs. plant size for a condenser pressure of 0.07 bar.

5.4. Variation of condenser pressure

Fig. 11. illustrates the effects of condenser pressure on the net electric efficiency of the plant. Decreasing the condenser pressure from 0.31 bar to 0.03 bar increases the net electric efficiency by 5.56 %.

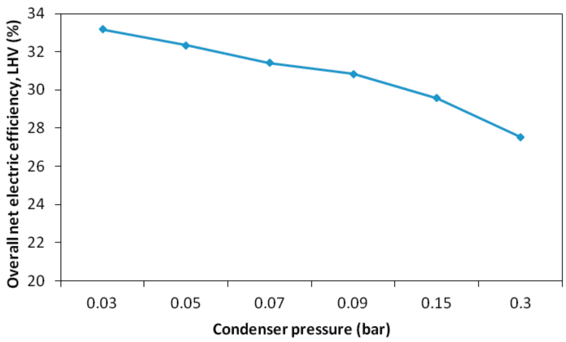

Fig. 11. Net electric efficiency vs. condenser pressure.

Conclusion

In this work a detailed modelling analysis of highly efficient Waste-to-Energy plants was performed and analyzed from the thermodynamic and technological features points of view. The analysis shows a suitable technical solution to achieve maximum efficiency of WtE plants for a rated thermal input of 186 MW_{LHV} by proposing a new configuration. Flue gas temperature at boiler exit, O_2 content at boiler exit, plant size and condenser pressure have a great impact on the net electric efficiency of the plant. High net electric efficiency without corrosion problems in the supereheater can be obtained by adopting a new steam cycle configurations. Some of the strategies considered in this paper to increase the net electrical efficiency are simpler, more economical and can be applied without considerable changes. Therefore, the proposed configuration with high steam parameters of 135 bar/ 540 ^{0}C leads to a net LHV efficiency of 33.19 %. This configuration has a relevant advantage compared with the conventional Waste-to-Energy plant since:

- It gives higher net electric efficiency without facing corrosion problems in the superheater.
- It makes economic sense by counterbalancing the increase in the cost of the Waste-to-Energy plants due to the increase in the overall net electric efficiency.

It is noteworthy that economic analysis must be performed in order to compare each of the aforementioned technologies in comparison with the proposed configuration. The authors have been proposed to perform the cost estimate analysis of the different configurations as future work.

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